

## Radio Astronomy

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## EXECUTIVE SUMMARY

Since Karl Jansky's first observations in 1932, improvements in technology have increased the sensitivity of radio telescopes by an average of about two orders of magnitude per decade, improved the angular resolution of radio images from tens of degrees to better than a thousandth of an arcsecond, and extended the short wavelength limit of radio astronomy from meter to millimeter and sub-millimeter wavelengths. The radio telescope is now the instrument of choice for high resolution and high fidelity images of many types of celestial objects.

During the past decade the unique facilities at the national radio observatories have made possible dramatic discoveries ranging from fundamental physics and cosmology to the spectacular radar imaging of asteroids. At the same time, pioneering observations made at millimeter and sub-millimeter wavelengths have provided the best picture yet of the spiral structure of our Galaxy, and have led to a much better understanding of the structure, dynamics, and chemistry of star-forming regions. New radio techniques have been developed to measure distances throughout the Universe. These methods are already leading to reevaluations of the size scale of the Galaxy and the Universe. Other advances in high resolution imaging, signal processing, and millimeter and sub-millimeter spectroscopy have opened many other new opportunities for radio astronomy in the 1990's. Unfortunately, however, the funding for radio astronomy has not been able to keep pace with the growth of the science.

*Over the past ten to fifteen years, important radio telescopes have been closed, and there has been minimal new capital investment in existing national facilities to upgrade them to the state of the art, or even to maintain them and replace obsolete instrumentation. Of particular concern are the deteriorating state of the VLA—the world's premier radio telescope—the inadequate support for the newly developed fields of millimeter and sub-millimeter radio astronomy, and the decrease in the number and level of research grants to individual scientists.*

As we enter the decade of the 1990's radio astronomy looks forward to the timely completion of the Very Long Baseline Array (VLBA), the Green Bank Telescope (GBT), the Arecibo upgrading project, the Arizona-German Sub-Millimeter Telescope (SMT), and the Smithsonian Sub-Millimeter Wavelength Array (SMA). Additional funds will be needed for operating these new facilities. At the same time, it is important to exploit the dramatic technical developments of the 1980's and to start now on the design and construction of facilities that will provide powerful new research opportunities during the decade following the 1990's.

*The Radio Astronomy Panel recommends as the highest priority for new instrumentation for radio astronomy the construction of a Millimeter Wavelength Array (MMA) with a collecting area about 2000 square meters, receivers operating in all atmospheric windows in the range of 30 to 350 GHz, angular resolution better than 0.1" at the shortest wavelengths, and versatile high resolution spectroscopic capability.*

The Millimeter Array will make possible the study of a wide variety of objects in the solar system, star formation and evolution, stellar nucleosynthesis, chemical and physical structure of the interstellar medium in the Milky Way as well as in distant galaxies, and the structure and evolution of the Universe. The sensitivity, angular resolution, speed, and image quality of the MMA will each exceed that of any existing millimeter wave instrument in the world by more than an order of magnitude.

Due to the fact that the MMA will not be complete before late in the decade, it is essential that adequate support be provided in the interim to the millimeter and sub-millimeter telescopes currently in operation. These instruments will advance the science and technology in this field during the next decade and train the young scientists who will use the MMA when it goes into operation. The existing university-based millimeter interferometers will play a particularly important role because they have begun and will continue to develop the scientific and technical program leading to the MMA. They will also provide a vital source of student and postdoctoral training in millimeter interferometry.

The Radio Astronomy Panel also recommends, in order of priority, the following new moderate scale instruments:

The construction of a filled aperture Large Millimeter Wavelength Radio Telescope.

The expansion of the VLA to cover the range of resolution intermediate between the current VLA and the VLBA, and to greatly enhance the imaging power of both the VLA and the VLBA.

The deployment in space of a 25-m class radio telescope, in collaboration with an international group of partners in Europe, Japan, and the USSR, to operate as a Very Long Baseline Interferometer (VLBI) element in space.

The Radio Astronomy Panel recognizes the need for a continuing opportunity for initiating new small-scale projects. Although the Panel fully expects that new ideas will be continually developed over the next decade, we have identified the following initiatives as being particularly meritorious at this time:

A Large Southern Radio Telescope in Brazil to be constructed and operated by an international consortium for research in atmospheric sciences, radio, and radar astronomy in the southern skies.

The construction of a small radio telescope especially designed to detect spatial fluctuations in the cosmic background radiation (CBR) at levels of one part in a million.

The participation in the Soviet and Japanese space VLBI missions planned for the mid 1990's.

The establishment of small research groups at universities to develop advanced instrumentation and carry out observational programs to search for extraterrestrial intelligence (SETI).

The development of a frequency agile, image-forming radio telescope for solar research.

The construction of a Fast All Sky Telescope to survey the sky for variable radio sources.

The Panel has identified the following areas of technological research which have particularly great potential to enhance the power of existing and future radio telescopes: a) the continued development of receiver technology for millimeter and sub-millimeter wavelengths; b) the development of broad bandwidth recording systems and data links for VLBI; and c) strengthening of efforts toward the protection from radio frequency interference (RFI) to ground, space, and lunar based radio telescopes, together with the development of effective techniques to suppress or eliminate the effects of RFI on radio astronomy observations.

The Panel also recognizes the opportunity for the development of major new capabilities that will be possible beyond the year 2000, and recommends that an orderly program begin during the 1990's directed toward the development of low frequency radio astronomy techniques on the ground and in space, ultimately leading to the establishment of a low frequency, high resolution radio astronomy telescope on the moon.

## Introduction

Radio astronomy began just before the second World War and matured in the 1950's, mostly through the pioneering efforts of scientists with backgrounds in radio science, electrical engineering, or wartime radar. Their work led to remarkable discoveries in the 1950's and 1960's, including radio galaxies, quasars, pulsars, radio bursts from the Sun and Jupiter, giant molecular clouds, interstellar masers, and the cosmic microwave background. The radio observations also led toward much better understanding of a number of other astrophysical topics, including the nature of planetary atmospheres, surfaces, and spin-orbit resonances, the physical conditions in star-forming regions, the importance of galactic nuclei, the gas content of circumstellar shells and interstellar space, and conditions in the most distant parts of the Universe corresponding to epochs shortly after its creation.

In the 1970's, radio astronomers undertook an ambitious radio telescope construction program to exploit these new astrophysical areas, as well as the vigorous development of the specialized technologies needed for such fruitful new techniques as very long baseline interferometry, millimeter wavelength spectroscopy, and fast data acquisition and signal processing for pulsar and planetary radar studies.

The techniques of radio astronomy have continued to develop rapidly during the 1980's. Specialized hardware and algorithms have been developed for aperture synthesis imaging, with angular resolution and image quality unequaled by any other technique, and for making detailed measurements of the weak periodic signals from pulsars. Lessons learned in long baseline interferometry experiments led to the construction of the transcontinental Very Long Baseline Array, with antenna elements located from Hawaii to the Caribbean. At the same time millimeter and sub-millimeter techniques have been developed and exploited in this nearly unexplored region of the electromagnetic spectrum. But, for more than a decade, NSF funding of ground-based astronomy has been inadequate to keep pace with the growth of the science. This has serious consequences which now threaten the health of all of astronomy in the United States. Radio astronomy, which depends on the NSF for nearly all of its support, is in a particularly critical situation.

*The lack of adequate funds for the support of individual scientists, for the operation, maintenance, and upgrading of existing radio telescopes to the state of the art, and for instrumentation and computing resources is the most important problem facing radio astronomy.*

As we enter the decade of the 1990's, opportunities for new research initiatives will depend on the timely completion of the VLBA, the GBT, the Arecibo upgrading project, the Arizona-German Sub-Millimeter Telescope, and the Smithsonian Sub-Millimeter Wavelength Array. Additional funds will be needed for operating these new instruments. At the same time, it is important to exploit the dramatic technical developments of the 1980's and to start now on the construction of radio astronomy facilities which will provide powerful new research opportunities during the decade following the 1990's.

## Scientific Opportunities

The history of radio astronomy has been characterized by the discovery of a wide range of fundamentally new phenomena and objects that have revolutionized our understanding of the Universe. Radio galaxies, quasars, pulsars, molecular masers, and solar radio bursts were serendipitous discoveries resulting from the use of powerful new technologies. Other new phenomena, such as gravitational lenses, neutron stars, and the microwave background radiation, were discussed prior to their discovery, but theoretical considerations played little role in their actual discovery.

Even among the more traditional cosmic bodies, such as stars, planets, and the Sun, radio observations have opened up a whole new domain of previously unknown phenomena. Planetary radio and radar observations first revealed the retrograde rotation of Venus and the unexpected rotation of Mercury. Other unexpected solar system discoveries include the excessive temperature of the Sun's corona, the high surface temperature of Venus likely the result of a runaway greenhouse effect, the high temperature of the outer planets apparently due to internal heat sources, the Van Allen Belts around Jupiter, and the spectacular low frequency bursts caused by violent electromagnetic activity in the atmospheres of Jupiter and the Sun.

For many years the analytic power of radio telescopes suffered from two major limitations: poor angular resolution and the inability to measure distances. But, during the decade of the 1980's, this situation has dramatically changed.

Because of the long wavelengths involved, it was thought for a long time that the angular resolution of radio telescopes must be severely limited compared with that of optical or infrared telescopes. In fact, the reverse is true; the long wavelength radio waves pass relatively unaffected through the terrestrial atmosphere while optical

telescopes are limited by "seeing." Also, because the precision needed to build diffraction limited instruments at radio wavelengths is not as demanding as at optical wavelengths, radio telescopes may have essentially unlimited resolution. Sophisticated new techniques for analyzing radio interferometer data effectively eliminate any effects of image distortion from the atmosphere to give radio images with extraordinary image quality and angular resolution better than one thousandth of an arcsecond. This is several orders of magnitude better than available by any other technique on the ground or in space.

Radio distance measurements are now able to reach beyond the local flow to give fundamentally new determinations of the size of the Galaxy, the Hubble Constant, and the size of the Universe itself. These techniques, some of which are completely independent of evolutionary effects or the usual hierarchical arguments, include: the direct trigonometric parallax of pulsars and other galactic objects; statistical parallax measurements of H<sub>2</sub>O masers; the time delay of OH emission in late type stars; VLBI measurements of supernovae expansion velocities; HI and CO spectroscopic redshifts; the Tully-Fisher Relation; VLBI observations of superluminal component motions; gravitational lensing; and the Sunyaev-Zeldovich effect.

#### *Millimeter and Sub-Millimeter Wavelength Astronomy*

Millimeter wave astronomy has opened up new opportunities to study the evolution of stars, galaxies, and the Universe itself. The chemistry and composition of the interstellar medium, the earliest stages of star formation, and the internal kinematics of luminous galaxies are uniquely revealed at millimeter wavelengths. Array-type radio telescopes for millimeter and sub-millimeter wavelengths, built with recently developed technology and exploiting powerful new imaging techniques, will provide tremendous improvements in sensitivity and resolution in these spectral bands.

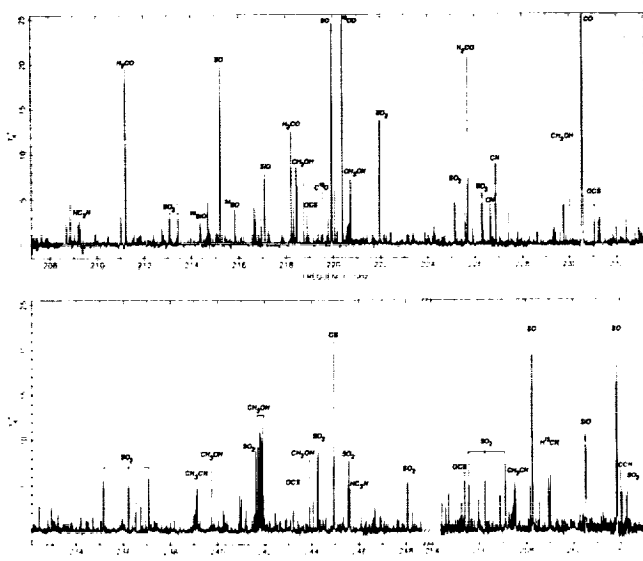


FIGURE 1 The millimeter wavelength spectrum of the Orion Molecular Cloud (OMC-1) showing more than one thousand lines identified with about thirty different molecular species. High resolution images of the chemical and isotopic distributions map the gradients of temperature and density, as well as the kinematics, and give insight into the process of how these clouds collapse to form stars. (Photo courtesy of T. G. Phillips, California Institute of Technology)

New stars are continually being born in giant clouds containing millions of solar masses of molecular gas. Studies of carbon monoxide made at 2.6 mm wavelength have led to the determination of the size, mass, and location of hundreds of molecular clouds throughout the Galaxy, and have provided the best picture yet of the spiral structure of the Milky Way. The study of isotope abundances in molecular clouds gives evidence for the survival of interstellar molecular material in primitive solar system objects, and allows the study of conditions relevant to the origin of the solar system, and perhaps, life itself. In the most luminous galaxies and quasars, the molecular gas appears to play a pivotal role in promoting energetic starbursts and possibly fueling active galactic nuclei.

Millimeter wavelength observations of the gaseous envelopes around very old stars give insight into their morphology, dynamics, nucleosynthesis and chemical abundance. High resolution millimeter wavelength images of outflowing envelopes of old giant stars show that they contain shells of gas containing molecules which must have been produced in a remarkably short time of a few thousand years. Improved sensitivity and resolution at millimeter and sub-millimeter wavelengths has also led to much better understanding of the structure, dynamics, and chemistry of star-forming regions, the detection of interstellar polyatomic organic molecules, and to the unexpected discovery of gaseous outflows from young stars.

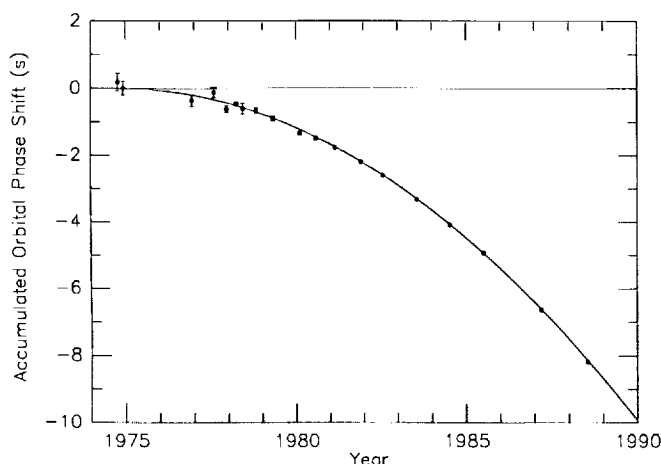
Millimeter and sub-millimeter wavelength observations are particularly critical to our understanding of galaxies, because these wavelengths penetrate the dust obscuring the galactic cores at other wavelengths and allow the large-scale gas and dust distributions and their relationship to global star formation to be determined. Carbon monoxide has now been detected in hundreds of galaxies, and imaged in dozens. The data reveal galaxies with central disks, rings, bars, strong nuclear concentrations, and prominent spiral arms. Molecular gas is found to be concentrated primarily in the inner parts of spiral galaxies, especially those that are very luminous in the infrared. The recent detection of CO in several quasars serves as a prominent indication of the future potential of extragalactic molecular astronomy.

#### *Meter to Hectometer Wavelength Astronomy*

During the past decade several unexpected discoveries have led to a resurgence of interest in radio astronomy at long wavelengths. Surprisingly, strong meter wavelength recombination lines have been found in the interstellar medium throughout the galaxy. A prominent meter wavelength continuum source led to the discovery of the first millisecond pulsar. The variability of Cassiopeia A at meter wavelengths is difficult to explain within the context of any conventional understanding. Solar radio bursts due to electron streams and shock waves have been observed and need to be imaged with high angular resolution, particularly in the nearly unexplored hectometer wavelength band where the radiation originates in the region of solar wind acceleration. Planetary radio observations at long wavelengths have also resulted in the recognition of a new coherent emission mechanism, known as cyclotron maser radiation, which provides an elegant explanation for the extraordinarily bright (up to  $10^{16}$  K) circularly polarized radiation seen in the Earth's auroral zones, from Jupiter and the other giant planets, from the Sun, and from a variety of stars. An important challenge for meter wave radio astronomy during the next decade will be the attempts to detect highly redshifted primordial "pancake" clouds of neutral hydrogen.

#### *The Sun, Stars, Pulsars, Interstellar Masers, and Extrasolar planets*

Millisecond and binary pulsars, formed in the complicated evolution of an interacting pair of stars, have taught us important lessons about the last stages of stellar evolution in close binary systems. Pulsars will continue to be extremely productive tools for probing a wide range of phenomena in gravitational physics, cosmology, astrometry, time-keeping metrology, and nuclear and plasma physics. The upgraded Arecibo antenna and the Green Bank Telescope, together with sophisticated new signal processing and data acquisition systems, will provide unprecedented sensitivity and flexibility for pulsar studies of all kinds.



**FIGURE 2** The emission of gravitational radiation by the binary pulsar PSR 1913+16 leads to an increasing change in the orbit compared with a hypothetical system whose orbital period remains constant. The observations agree to better than one percent with the change predicted from general relativity and provide the only experimental evidence for the existence of gravitational radiation. (Photo courtesy of J. H. Taylor, Princeton University)

Molecular maser clouds are found surrounding newly formed as well as very old stars. Measurements of Zeeman splitting of OH and H<sub>2</sub>O maser lines determine the magnetic field strength which has been important in understanding the energy balance and kinematics of the molecular clouds. Astrometric VLBI measurements made with the extraordinary precision of 10 microarcseconds per year have made it possible to track the motions of H<sub>2</sub>O masers in the envelopes of young stellar objects, and to determine directly their distances. Extension of this technique to space VLBI offers the promise of the direct measurement of distances to nearby galaxies and the recalibration of the distance scale of the Universe.

The high sensitivity of the Very Large Array and the Arecibo telescope has also made possible the detection and imaging of radio emission from a variety of stars. Radio emission with a thermal spectrum has been identified with stellar winds which transfer mass between the components in binary star systems, while non-thermal emission is associated with a wide range of phenomena including short-lived flares up to a million times more intense than those seen on the sun. The VLA has identified the locations where high energy electrons are accelerated and confined during solar flares, and has revealed a remarkable correlation between radio brightness and the magnetic field structure of the chromosphere and corona. The Millimeter Array and the added resolution of the expanded VLA will be particularly important in imaging the radio emission from stars of every spectral type and luminosity.

Interest in the existence of planets around other stars and their possible consequences has never been higher. Astrometric detection of dark stellar companions may be possible with the VLBA. The formation of planetary systems around individual stars is a fundamental problem that is best studied at millimeter wavelengths where the dynamics and chemistry of the dust and gas surrounding newly formed stars can be directly observed. The millimeter and sub-millimeter arrays and the Large Millimeter Telescope will be extremely powerful tools for probing preplanetary circumstellar disks. In addition, the Search for Extraterrestrial Intelligence, SETI, continues to fascinate the layman as well as scientists. SETI provides a powerful intellectual and technical challenge, and will be expanded during the 1990's with powerful new instrumentation and techniques that will greatly extend the horizons of the search.

#### *The Planets, Asteroids, and Comets*

With the detection of Pluto, thermal radio emission has now been observed from all of the planets, several of their satellites, and from a number of asteroids and comets. Millimeter interferometry of ammonia in the atmosphere of the giant planets and of carbon dioxide in the atmospheres of Venus and Mars offer the possibility to directly observe the diurnal, latitude, and seasonal variations of atmospheric temperature and molecular abundance. Variable sulfur dioxide emission has been observed at millimeter wavelengths on Io, probably as a result of volcanic activity. Millimeter observations of hydrogen cyanide, a cometary parent molecule, provides direct information on the kinematics in cometary coma as well as on its chemical composition.

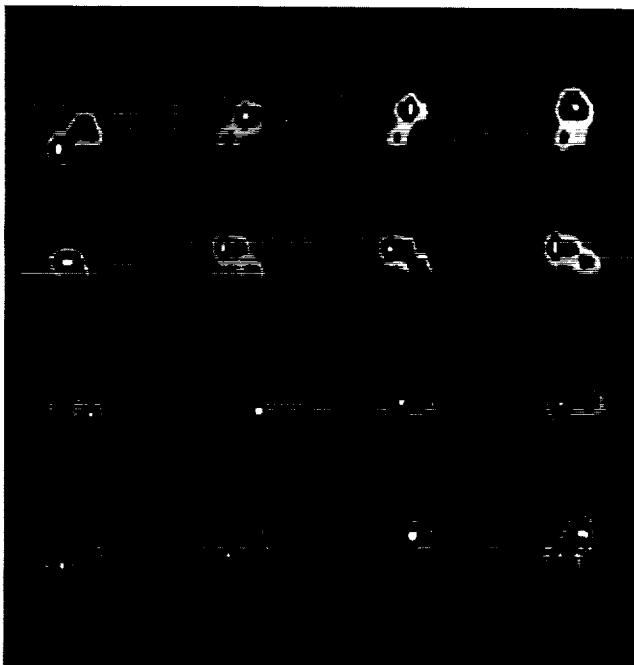


Figure 3 Radar images of asteroid 1989 PB made at the Arecibo Observatory near the time of closest approach of 2.5 million miles. The dumbbell-shaped asteroid is between one and two kilometers across and rotates with a period of about four hours. These images have an effective resolution of better than ten milliarcseconds. (Photo courtesy of S. Ostro, Caltech Jet Propulsion Laboratory)

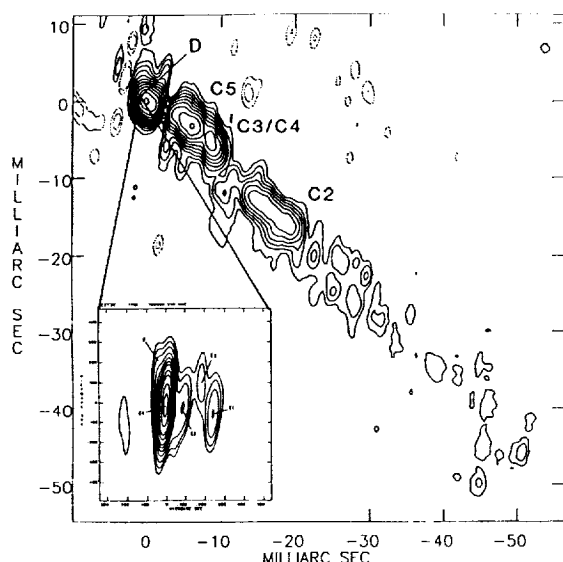
Worldwide VLBI observations have been used to track the two Soviet VEGA balloons to give information on the circulation of winds in the atmosphere of Venus. Radar observations during the past decade have yielded the first direct detection of a cometary nucleus, the discovery of large-particle clouds associated with comets IRAS-Araki-Alcock and Halley, the extremely irregular, non-convex shapes of some near-Earth asteroids, and the first direct evidence that the rings of Saturn contain centimeter or larger sized particles.

### Radio Galaxies, Quasars, and Cosmology

Radio observations continue to play a key role in understanding galaxies, quasars, and active galactic nuclei (AGN's), and have changed our understanding of cosmology in a fundamental way. Observations of neutral hydrogen gas in thousands of galaxies have revealed the existence of structures with dimensions of at least 50-100 Mpc. These results establish important boundary conditions on the evolution of large-scale structures in the Universe, and have been used for dynamical studies of the mass distribution within galaxies, placing lower limits on the amount of "dark matter" that they contain. Extragalactic neutral hydrogen and carbon monoxide surveys will continue to be extremely productive, especially with the upgraded capabilities of the Arecibo telescope, the VLA, the new Green Bank Telescope, and the proposed new millimeter radio telescopes. The observation of highly redshifted atomic and molecular gas provides information about conditions in galaxy disks at early epochs. Together with optical redshift surveys, these data provide an invaluable pool of cosmological information to investigate the formation, evolution, and large-scale distribution of galaxies, and to address the question of whether the Universe is open or closed. Gravitationally focused images of distant quasars give us a new technique for studying the mass distribution in galaxies as well as a new and potentially important method of determining the size and age of the Universe.

Probably the most important discovery in cosmology in modern times is the radio detection of the cosmic microwave background radiation. Except for the effect of our motion through the Universe, the background radiation is found to be remarkably smooth to within a few parts per hundred thousand. This simple experimental fact provides one of the most stringent constraints on models of the early Universe, and particularly on the enigmatic process of galaxy formation. Testing the isotropy of the cosmic microwave background at the one-part-per-million level is now experimentally feasible and needs to be vigorously pursued. This type of experiment will continue to be one of the observational cornerstones of cosmology.

Long-standing problems still remain in understanding the source of energy in quasars and active galactic nuclei, and the conversion of energy into the relativistic plasma which generates the observed synchrotron radiation. VLA observations during the past decade have revealed jets, filaments, and hot spots in both extragalactic radio sources and in the center of our own Galaxy. These complex structures reflect the wealth of detail in the radio emitting plasma and the important role played by magnetic fields.



**FIGURE 4** Six centimeter VLBI image of the core of the quasar 3C 273 made from a 14 element "world-array." The image has an angular resolution of 1 by 2 milliarcseconds. Repeated observations at this and at shorter wavelengths show the ejection of superluminal components which emerge from the core and appear to move along a fixed curve path with similar speeds of about one milliarcsecond per year. This corresponds to an apparent transverse linear velocity of about ten times the speed of light, and is referred to as *superluminal motion*.

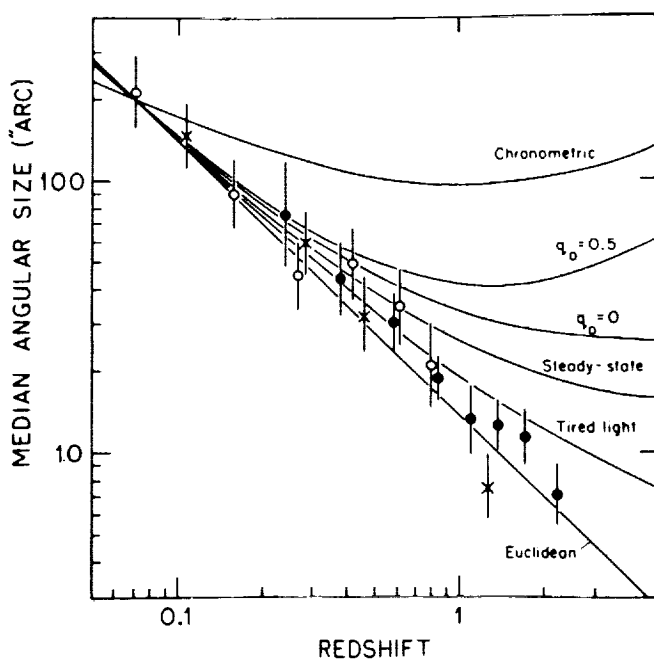
The insert shows the core component observed at 3 mm wavelength with an angular resolution about ten times better than at 6 cm. Millimeter interferometry gives the highest resolution images ever obtained in astronomy. The individual components are less than half a light year in extent. (Photo courtesy of L. Baath, Onsala Space Observatory, Sweden)

VLBI observations have concentrated on the small but incredibly energetic cores of quasars and active galactic nuclei where the relativistic plasma is accelerated and focused into narrow jets which flow with apparent superluminal motion toward the extended radio lobes located hundreds of thousands of light years away. Superluminal motion is thought to be due to bulk relativistic motion of the radiating plasma nearly along the line of sight. An important consequence of the relativistic motion is that the synchrotron radiation is beamed along the direction of motion, so that the apparent radio luminosity of quasars and active galactic nuclei is very dependent on the orientation of the beam and in favorable cases may be enhanced by orders of magnitude. It is not clear how important the effects of relativistic beaming are in other parts of the electromagnetic spectrum, but the correlation of time variability and the continuity of the spectra suggest that the apparent optical, IR, and X-ray luminosity of quasars and active galactic nuclei may also be enhanced by this phenomenon. But the

beaming models are difficult to reconcile in detail with the observations, and attempts to establish unified geometric models have been only partially successful. The increased resolution, sensitivity, and dynamic range expected from the expanded VLA, the VLBA, and space VLBI experiments will provide greatly enhanced capabilities for attacking these problems.

### *Challenges For Radio Astronomy in the 1990's*

Many astrophysical puzzles are not yet solved, and almost certainly some presently "known" answers are wrong. The apparent neutral hydrogen links between the distant quasars and nearby bright galaxies, the apparent anisotropy and anomalous nature of the counts of strong radio sources, the absence of expected relativistic effects in the angular size-redshift distribution of quasars, and the apparent quantization of quasar and galaxy redshifts, are all difficult to understand within the framework of conventional cosmology and astrophysics.



**FIGURE 5** Angular size - redshift relation for different samples of radio galaxies and quasars compared with various world models. The only simple model consistent with the data is the static Euclidean model. Friedmann models require that the evolution of linear size with cosmic epoch just compensate the geometric effects to reproduce the Euclidean relationship. (Photo courtesy of V. Kapahi, Tata Institute, Bangalore, India)

By its very nature, basic scientific research addresses questions that lie at the boundaries between the known and unknown. If an answer to a scientific question is predictable with any degree of confidence, the question is probably not very close to this boundary! For this reason, it is difficult and probably even inappropriate to speculate on the most important scientific advances during the coming decade, even if the discussion is in rather general terms and the time scale is the relatively near future.

Too great a reliance on detailed planning may limit truly innovative thinking. We note that many of the radio astronomy highlights of the 1980's—millisecond pulsars and the detection of gravitational radiation damping, the extreme isotropy of the cosmic background radiation, the ordered clumpiness of the distribution of galaxies, bi-polar outflows from very young stars, gravitational lensing, and the high-dynamic-range mapping capability of the Very Large Array—were unexpected developments and largely unforeseen before their discovery. Earlier, radio galaxies, AGN's, quasars, pulsars, radio bursts from the Sun and Jupiter, the high surface and atmospheric temperatures of the planets, giant molecular clouds, interstellar molecular masers, and the cosmic background radiation itself were initially discovered as a result of the drive to exploit emerging new technology. Considerations of specific scientific issues had little impact on these major discoveries which now dominate much of our astrophysical thinking. As a result of these discoveries, radio astronomy has probably generated more new problems and questions than it has solved old problems, and has shown not only the inadequacy of our understanding even a few decades ago but, more importantly, the inadequacy of the questions we were asking. In an experimental discipline like radio astronomy, progress depends on the availability of the most advanced technology used by talented people with access to the best possible opportunities for training.



### Recommendations for New Facilities

*The Radio Astronomy Panel recommends as the highest priority for new construction a Millimeter Wave Array with sub-arcsecond resolution, comparable to that of the VLA and having good image quality, a sensitivity adequate to study faint continuum and line emission, and a flexible spectroscopic capability in all of the millimeter wavelength windows between 30 GHz and 350 GHz. Cost: \$115 M.*

The Panel also identifies the following moderate sized projects, in order of priority, as being complementary to the Millimeter Array and important to the continued development of radio astronomy during the decade of the 1990's.

A Large Millimeter Radio Telescope Working to at Least 230 GHz <sup>1</sup>	\$ 15 M
Expansion of the VLA	\$ 33 M
A VLBI Antenna in Space <sup>2</sup>	\$ 200 M

The Panel recognizes the need for a continuing opportunity to develop small new instruments and programs in response to newly developed discoveries, techniques, or theoretical ideas. The following small new initiatives at university facilities and national laboratories have been identified as being particularly important and timely.

A Large Southern Radio Telescope to be Built and Operated in Brazil in Collaboration With an International Consortium of Partners <sup>3</sup>	\$ 10 M
A Dedicated Cosmic Background Imager	\$ 10 M
RADIOASTRON and VSOP Space VLBI Missions <sup>4</sup>	\$ 10 M
Establishment of University-Based SETI Research Programs	\$ 5 M
A Fast All Sky Telescope	\$ 10 M
A Solar Radio Telescope	\$0.4 M

The Panel also recognizes the importance of developing long-range plans and instrumentation needed for new facilities in the beginning of the 21st century, including:

The identification of technological innovations leading to the development of new instrumentation for radio astronomy, including receiver technology for millimeter and sub-millimeter wavelengths, broadband recording systems for VLBI, advanced computing facilities and algorithms for imaging and pulsar analysis, and the strengthening of efforts to control radio frequency interference.

Radio telescopes in space for observations at sub-millimeter wavelengths

An astrophysical observatory in Antarctica with large millimeter and sub-millimeter radio telescopes

A low frequency radio telescope on the far side of the moon

<sup>1</sup> Federal share representing about half of the total cost of project.

<sup>2</sup> Approximate US share of proposed international mission

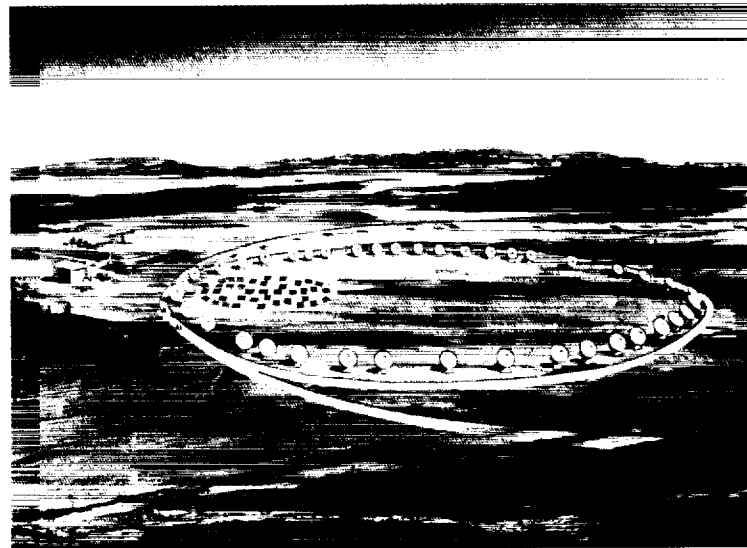
<sup>3</sup> US share of approximately \$ 100 M project

<sup>4</sup> Cost of US participation in Soviet and Japanese space VLBI missions

### *The Millimeter Array*

Large radio telescopes may require a decade to design and construct. In order to ensure the continued preeminence of American radio astronomy into the next decade, it is important to begin now the work leading to the next generation of radio telescopes.

*The highest priority of the Radio Panel for new instrumentation is for the construction of a Millimeter Wavelength Array with sensitivity, resolution, image quality, and speed adequate to investigate the wide range of astrophysical phenomena that are best studied at millimeter wavelengths.*



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FIGURE 6 Artists conception of the Millimeter Array showing the antennas in the 250 meter configuration. The road for the 900 meter configuration is shown as well as the compact configuration in which the antennas are arranged to simulate the response of a single 70 meter diameter antenna. The 3 km outer road is coincident to the 900 meter road in this inner part of the array. (Photo courtesy of the National Radio Astronomy Observatory—Associated Universities, Inc.)

Dramatic advances in technology have caused an explosive growth of millimeter and sub-millimeter wave astronomy. The high spectral resolution provided by heterodyne spectroscopy of molecular clouds provides a powerful tool for basic molecular physics. Of particular interest is the chemistry of the interstellar medium, which is readily studied at millimeter wavelengths where the spectroscopy of cosmic molecules rivals in richness the Fraunhofer spectrum of the sun and stars. Observations of these lines play an important role in helping to understand how molecular clouds collapse to form stars, to identify the molecules primarily responsible for cloud cooling, and to determine the kinematic details of the process from the observed velocity fields. One very important result will be a great improvement in our understanding of star-forming regions in our own and other galaxies.

Millimeter astronomy was developed and pursued solely in this country until the early 1980's. Although no large millimeter wavelength instrument has ever been built by the United States, major facilities are now in operation in Europe and in Japan. The Millimeter Array will recapture the once dominant position of the United States in millimeter astronomy and will complement the major U.S. instruments that will be in operation by the end of the next decade in other wavelength bands.

The MMA will be especially well-suited to simultaneous multi-wavelength spectroscopy with high spectral resolution and will have a wide range of astrophysical applications, including solar system research, molecular spectroscopy, studies of protoplanetary systems, star formation, primordial galaxies, and the microwave background.

In the most distant parts of the Universe, the MMA will image thermal dust emission in galaxies out to redshifts of ten, yield images of dust emission in active galactic nuclei and quasars with a resolution about one hundred parsecs, detect carbon monoxide from galaxies out to large redshifts, and image the Sunyaev-Zeldovich effect from clusters of galaxies to provide an independent determination of the Hubble constant and the size and age of the Universe.

For nearby galaxies, the MMA will determine the masses and kinematics of optically obscured galactic nuclei with a resolution of a few parsecs, and image the distributions of the molecules containing carbon, oxygen, nitrogen, and sulfur and their isotopes.

Within the Galaxy, the MMA will observe stars of every spectral type and luminosity class, measure their photospheric emission and temperature gradients, and determine positions with astrometric accuracy. Observations with 0.1 arcsecond resolution will permit the identification of regions of star formation in dark clouds, resolve cloud fragments, protostars, and circumstellar accretion disks as small as 10 AU, image the density and velocity structure of protostellar and pre-planetary disks, and provide images of the chemical gradients in protostellar nebulae and circumstellar shells that reflect the chronology of stellar nucleosynthesis and envelope convection,

Inside the solar system, the MMA will probe the physics of particle acceleration in solar flares; image the atmospheric winds and the temperature profiles of Venus and Mars; resolve the phosphine emission in the Great Red Spot on Jupiter, hydrogen cyanide on Titan, and volcanic emission on Io; and obtain unobscured images of cometary nuclei, asteroids, and the Pluto-Charon system.

The Millimeter Array will be a national facility open to all qualified users, and will provide fast sensitive high fidelity sub-arcsecond imaging from 30 GHz to 350 GHz, wide-field imaging, sensitive simultaneous broadband operation, and a comprehensive "single-dish" capability. The proposed array will contain 40 transportable antennas, each 8-m in diameter, and will be reconfigurable to match the angular resolution to a wide range of astrophysical problems. The angular resolution will be  $0.07 \lambda_{\text{mm}}$  arcsecond in the largest 3-km configuration. In its compact configuration, the MMA will have a resolution comparable to that of a 70-m antenna with a collecting area equal to that of a single 50-m diameter antenna. The rms sensitivity for point source continuum observations will be better than  $1 \text{ mJy}/(\text{min})^{1/2}$ , and for spectral line observations at 230 GHz,  $1.2 \text{ K}/(\text{min})^{1/2}$  for a 1" beam and 1 km/sec velocity resolution. Design and prototyping work for the MMA is planned for the period 1991-1994, and construction from 1994-1998.

#### *Medium Scale New Instruments:*

**Large Millimeter Wave Telescope:** The Radio Astronomy Panel recognizes the need for a modern 50-meter class filled aperture radio telescope capable of operation to at least 230 GHz, located at a good site and available to scientists independent of their institutional affiliation. The Panel is impressed by the progress being made in the use of active optics to build a large millimeter radio telescope at relatively low cost. Such an instrument equipped with focal plane heterodyne and bolometer arrays will offer a huge increase in speed and sensitivity over currently available instruments and will provide an extremely powerful tool for the study of interstellar matter and star formation. The Large Millimeter Telescope will allow fast spectroscopic and continuum surveys of large regions of the sky, and may have application to planetary radar. The LMT will also provide a substantial enhancement to millimeter VLBI. It is expected that the LMT will cost about \$35 M to construct, with about half of this to be paid by private or state funds.

**VLA Expansion:** The gap between the VLA and the VLBA may be bridged with a combination of tape recorder and fiber optic links between the two arrays and by adding new antenna elements. This will increase the resolution of the VLA at all frequencies; improve the dynamic range, field of view, and extended source sensitivity of the VLBA; and give a "scaled array" capability over a much wider range of frequencies than is now available. Of particular importance will be the ability to determine how the Stokes parameters of the radiation vary with frequency over a wide range of frequency at a fixed angular resolution. The Radio Panel recommends a phased plan which includes: (a) placing up to four VLBA tape recorders at the VLA (\$1 M); (b) constructing up to four new antennas in New Mexico and Arizona (\$21 M); (c) providing fiber optic links from the VLA to the four new antennas and to the one at Los Alamos, and expanding the VLA correlator from 27 to 33 stations (\$11 M). These improvements will provide a greatly enhanced resolution and imaging capability over a wide range of frequency, and brightness sensitivity with many applications to radio observations of the Sun and planets, radio emission from stars, novae, protoplanetary nebulae and stellar winds, as well as from star-forming regions, and for the study of active galactic nuclei and quasars.

**Space VLBI:** The VLBA will give the highest resolution images of any astronomical instrument, and further improvement can be obtained only by going into space. Recent experiments using the TDRSS satellite have demonstrated the feasibility and power of space VLBI. Space VLBI was among the 1982 Astronomy Survey

Committee recommendations for "moderate new programs," but NASA has been slow to participate in any of the space VLBI missions planned for the 1990's.

The International VLBI Satellite (IVS) is being discussed by European, Soviet, Japanese, and U.S. radio astronomers for a possible launch near the end of the decade. IVS will include a 25-meter class antenna working to wavelengths as short as 3 mm located in high Earth orbit at altitudes between 20,000 and 150,000 km. IVS will provide an order of magnitude or more improvement in sensitivity and image resolution over the Japanese and Soviet missions planned for the mid 1990's. It will also be capable of sensitive, single aperture, spectroscopic observations of molecular oxygen in the 60 GHz band from above the earth's atmosphere, which is opaque at this frequency. Knowledge of molecular oxygen abundance, which is very uncertain, is important to understanding the chemical and dynamical evolution of molecular clouds.

IVS is being planned as an international facility which will include the participation of ground-based radio telescopes throughout the world. The current baseline for the study contains an ESA antenna and a Soviet service module and Energia launch vehicle. Other variants are possible which include a substantial US involvement, for example, a U.S. service module and part of the experimental package. The Radio Astronomy Panel considers space VLBI to be the highest priority project for radio astronomy from space during the 1990's, and it is important that the US take an active role in the early planning and mission definition studies for an international VLBI satellite.

### *Small-Scale Projects*

*The Panel recognizes the need for a continuing level of support for small-scale programs that can react to the rapidly changing developments in radio astronomy. We describe below several important areas which we are able to identify at this time. We do not prioritize these small-scale initiatives because we fully expect that new meritorious ideas will arise on a time scale less than that of the next decade review, and that the selection of specific programs should depend on normal agency review and the nature of funding opportunities as they arise.*

**Large Southern Radio Telescope:** Many important research programs require the highest attainable instantaneous sensitivity, and thus the largest possible collecting area. All of the biggest radio telescopes in the world are located in the northern hemisphere. The construction of a large aperture radio telescope in the southern hemisphere will give a powerful new capability for research in the southern skies, including atmospheric studies, access to solar system objects invisible from the north, the galactic center region, the Magellanic Clouds and the southern extragalactic sky. The recent design and construction of Gregorian subreflector systems, conducted as part of the project for upgrading the Arecibo telescope, show the great potential of modern applications of spherical antenna technology for achieving very large collecting area.

The proposed LSRT will work at short centimeter wavelengths and will have a collecting area comparable to that of the upgraded Arecibo telescope. A novel feed arrangement will give a wide declination range covering most of the southern sky. It is expected that the LSRT will be built and operated in Brazil by an international consortium, at a total cost of about \$100 M and a cost to the United States about \$10 M.

**Cosmic Background Imager:** The cosmic background radiation is perhaps the most important tool of observational cosmology. On angular scales greater than a few degrees, the background radiation reflects directly conditions in the early Universe at an age of only one hundred thousand years. On smaller angular scales, it may be distorted, both spatially and spectrally, by various processes connected with gravitational collapse and the formation of galaxies and other large-scale structures. Upper limits on the anisotropy are now at a level of a few parts in a hundred thousand. If anisotropies are not found at a level of a few parts in a million, then our basic understanding of the early Universe may need to be fundamentally revised.

Recent technological advances in the design of reliable low-noise bolometers and heterodyne receivers suggest that it is possible to reach the required levels of sensitivity with radio telescope systems especially designed for this problem. One possible approach is to use an array of about 50 horn antennas to eliminate the confusing effects of ground and atmospheric radiation. Another option is to use an array of bolometers located in the focal plane of a millimeter radio telescope. Such instruments will also be powerful tools for accurately measuring the microwave decrement due to the Sunyaev-Zeldovich effect. When combined with accurate X-ray data, these measurements will yield an entirely independent determination of the Hubble constant and the size and age of the Universe.

**RADIOASTRON and VSOP:** The USSR and Japan are each planning to launch VLBI satellites in the mid 1990's. U.S. scientists have been involved from the start in defining these missions, and many Eastern and Western European countries, Australia, and Canada are participating in various ways in their implementation.

In order to exploit the unique opportunities made possible by these foreign space VLBI missions, as well as to develop the necessary skills and expertise needed to plan for a future U.S. space VLBI mission, the Radio Astronomy Panel recommends that the large U.S. ground-based radio telescopes be made available as elements of the Earth-Space interferometer, that VLBA compatible recorders be supplied at Soviet and U.S. ground stations used to receive data from the space element, that U.S. radio telescopes be equipped to provide local oscillator and data links to the foreign spacecraft, and that U.S. scientists participate fully in developing and carrying out the VSOP and RADIOASTRON scientific programs.

The overall level of support for space VLBI in the next decade is expected to be about half a billion dollars, primarily in Japan and the USSR. Although VLBI techniques were developed in this country, and the only successful space VLBI experiments so far have been done with an U.S. satellite, there is no planned U.S. space VLBI mission. Fortunately, U.S. astronomers can fully share in the scientific returns of the Japanese and Soviet missions with a relatively small financial investment. Since the U.S. will have no involvement in the design, construction, or launch of any space hardware or in mission management, the Panel suggests that U.S. participation be handled through conventional grants to the participating scientists rather than administered as a NASA project.

**Search for Extraterrestrial Intelligence:** The Search for Extraterrestrial Intelligence (SETI) will be an exciting intellectual and technical challenge for the next decade. A successful "contact" would be one of the greatest events in the history of mankind. We are the first generation that could realistically succeed, and there is great public interest in SETI. The major issue is the appropriate level of resources to devote to SETI and how these resources should be divided between a large centrally managed program and the more traditional university-based research efforts. SETI is not part of radio astronomy, but the tools of radio astronomy are used for SETI, and radio astronomers have pioneered the development of observational SETI programs.

NASA has initiated the *Microwave Observing Project* which will begin searching in 1992 and last until the end of the decade. The MOP will expand the volume of parameter space investigated (direction, frequency, polarization, sensitivity) by many orders of magnitude over what has been done in the past. The search consists of two complementary strategies: the Sky Survey which will use 34 meter DSN antennas to scan the entire sky between 1 and 10 GHz, and the Targeted Search using the world's largest radio telescopes to examine about 800 nearby solar-type stars between 1 and 3 GHz. The *Microwave Observing Project* will be the first truly systematic SETI exploration of the microwave region of the spectrum and will cost about \$100 M over the rest of the decade.

The Radio Astronomy Panel recommends the establishment of a university-based SETI research program to develop new ideas and architectures for signal processing algorithms and processors, to develop search strategies, to implement innovative new hardware, and to establish search programs complementary to the NASA *Microwave Observing Project*. The proposed new program would provide a medium for the exchange of new techniques and hardware and the training of students in advanced signal processing techniques, as well as a means to pursue a viable observational program. Present levels of support to the scientific community are of the order of \$100 K per year, which is inadequate to sustain a productive effort. The Panel recommends that university-based SETI research be supported at an annual level of about \$500 K which would be adequate to support one or two independent research groups, each with four or five undergraduate, graduate, and post-doctoral researchers.

**Solar Radio Astronomy:** The VLA, Arecibo, and the proposed Millimeter Array are powerful instruments for solar research, but the existing instruments lack frequency agility. The Panel recommends that consideration be given to equipping the VLA and Arecibo Telescopes with frequency agile receivers and feeds. Opening up the full radio spectrum will provide powerful diagnostic information, not only for the sun, but for a wide variety of stellar, galactic, and extragalactic objects as well. The Panel also endorses the planned extension of the solar-dedicated, frequency-agile array at the Owens Valley Radio Observatory.

**Fast All Sky Radio Telescope:** FAST is a proposed array of twenty 3-meter antennas which will monitor most of the sky at centimeter wavelengths with an rms sensitivity of 10 mJy in one or two days. It will be used to study time variability in compact active galactic and extragalactic radio sources. FAST will be the only high-resolution, all-sky monitoring instrument available in any spectral band.

## Continuing Activities and Projects Already Underway

### *Facility Operation and Maintenance, Upgrading of Telescopes and Instrumentation*

NSF support for radio astronomy has been inadequate for the operation, maintenance, and upgrading of the national and university-operated radio observatories and for the modernization of instrumentation and computing resources at these facilities. Of particular concern is the deteriorating state of the VLA, the inadequate support for millimeter and sub-millimeter astronomy, and the need for modern computing facilities.

By far the most powerful and most productive radio telescope in the world is the VLA with its extraordinary speed, sensitivity, resolution, and image quality. Since there have not been adequate funds for even the most basic maintenance, the railroad track, power distribution system, antenna structures, and other aspects of the physical plant are deteriorating. Much of the instrumentation of the VLA uses 15-20 year old technology because there has not been the refurbishment and upgrading at the level appropriate to a scientific instrument of this size, sophistication, and productivity.

*The operation and maintenance of the VLA needs to be brought to a level appropriate to its broad scientific impact and great capital investment, and the seriously out of date instrumentation needs to be replaced with modern low-noise radiometers, fiber optic transmission lines, and a modern broad band correlator. These upgrades will improve the sensitivity by up to an order of magnitude, improve the frequency coverage and spectral resolution, and increase the maximum allowable image size.*

As a result of the years of inadequate support, it will now cost about \$40 M to incorporate these badly needed modernizations. This is comparable in cost to the moderate sized ground-based projects being considered by the Survey Committee. However, spread over eight years, it represents a level of investment corresponding to two to three percent per year of the replacement cost of the VLA/VLBA. Routine maintenance and modernization programs of this type and at this level would normally not be included in a discussion of major new facilities, but the situation has become critical and has risen to a high level of visibility because of the nearly complete absence of funds for this purpose since the completion of the VLA about a decade ago.

In many respects the VLA dramatically exceeds its performance at the beginning of the previous decade. The speed is faster by a factor of two, image size is larger by a factor of four, the maximum dynamic range has been improved by a factor of 50, the number of spectral line channels has been increased from 8 to 512, and mosaic images larger than the primary beam of the antenna are now being made. These scientifically important gains in performance have come as a result of powerful new algorithms but at the cost of greatly increased computing requirements. As a result, the computing situation for the VLA has been critical for some years, and many excellent scientific programs are not done because of inadequate computing facilities. The power of the VLA system, the complexity of modern data reduction algorithms, and the need to annually support more than six hundred users now overwhelms the available computing capacity at the NRAO and elsewhere. Full exploitation of the power of the VLA and VLBA will require new hardware and software that can be readily shared between the arrays and their user sites, the installation of small supercomputers and imaging workstations at the VLA/VLBA operations center and in university laboratories, and the establishment of effective interfaces to the large supercomputer centers for the most CPU-intensive data.

The Panel also recognizes the exciting opportunities available during the 1990's for research at millimeter and sub-millimeter wavelengths made possible by recent developments in technology in this newly opened region of the radio spectrum, the need to aggressively develop the technology necessary for future instrumentation at millimeter and sub-millimeter wavelengths, and the need to maintain and expand the pool of skilled millimeter wavelength scientists. The upgraded Haystack radio telescope and the new Green Bank Telescope will provide powerful new opportunities at longer millimeter wavelengths, while the Caltech and MPI-Arizona sub-millimeter telescopes will continue to have unique capabilities, even after the completion of the MMA.

*The existing millimeter and sub-millimeter radio telescopes and especially the millimeter wavelength interferometers need to be extended and enhanced, instrumentation based on the most advanced technology needs to be developed for these facilities, adequate support given for their operation, and additional resources made available to make these instruments accessible to a broad group of scientists independent of their institutional affiliation.*

*Projects Already Underway:*

At the beginning of the 1990's, five major radio astronomy projects are already underway. The timely completion of these instruments and provision for adequate funds for their operation will give tremendous improvements in the angular resolution, sensitivity, and frequency coverage over now existing radio telescopes, and will ensure the vitality of U.S. radio astronomy during the decade of the 1990's.

**Very Long Baseline Array:** The VLBA is a major new aperture-synthesis user facility in the form of a 10-element transcontinental array capable of imaging at the sub-milliarcsecond level. Construction of the VLBA received the highest priority for major new ground-based instruments in the 1982 Astronomy Survey Committee, and the project received initial funding in 1984. Annual funding at a much lower level than originally planned has extended the construction time from four years to nearly a decade. The first several antennas in the array are complete. Additional elements will be completed at a rate of two to three per year, but may not be fully utilized due to limited operating funds. The expected completion date for the full array is now 1992, five years later than originally planned.

**Arecibo Upgrade:** The Arecibo 1000-foot radio telescope has by far the largest collecting area of any centimeter wavelength facility in the world. Major improvements now in progress will provide significant enhancement of nearly all capabilities of the telescope for radio and radar astronomy and for atmospheric research. At present the spherical aberration of the telescope's primary mirror is corrected by using line feeds with inherently narrow bandwidths. Ingenious ideas behind a broad-band Gregorian feed system for Arecibo were first discussed a decade ago. Many details of a practical design were worked out over the next few years, and the concept was proven with detailed physical-optics computer modelling. A scaled-down "mini-Gregorian" feed system was put into operation in 1989. Tests have shown that this system efficiently illuminates a 350-foot portion of the Arecibo reflector and behaves in every way as expected. Funding for the full upgrading project, which will improve the sensitivity by a factor of 3 to 40 and will be cost-shared between NSF and NASA. Completion is expected in 1993. The enhanced telescope will have continuous frequency coverage between 0.3 and 8 GHz, with unprecedented instantaneous sensitivity.

**Green Bank Telescope:** The construction of a large, fully steerable, filled aperture radio telescope has been endorsed by essentially every review of the needs of U.S. radio astronomy. The 1982 Astronomy Survey Committee Radio Panel recommended an instrument in the 100-meter class which would work to wavelengths at least as short as one centimeter as an important priority for the 1980's. Following the collapse of the Green Bank 300-foot antenna in late 1988, NRAO accelerated its design study for a fully steerable, filled aperture instrument. The GBT is being designed with a novel "clear aperture" feed support system to reduce the effect of unwanted signals and active optics to permit use at wavelengths at least as short as 7 mm and possibly to even shorter wavelengths. A special congressional appropriation made funds available to NSF for the construction of the GBT, which is expected to be in operation by 1995.

**The-Submillimeter Telescope (SMT):** The University of Arizona Steward Observatory, and the Max Planck Institut fur Radioastronomie, FRG, are constructing a 10 meter diameter precision radio telescope to be located at an altitude of 3180 meters (10,425 ft) on Mt. Graham 75 miles northeast of Tucson. The SMT will use carbon-fiber-reinforced-plastic to achieve an overall surface accuracy of 15 microns. When completed in 1992, it will be the largest telescope with good performance at wavelengths as short as 350 microns. Funds for the construction and operation of the SMT are being provided primarily from the MPIfR and the University of Arizona.

**Sub-Millimeter Wavelength Array:** The Smithsonian Astrophysical Observatory is building the world's first sub-millimeter array, which will consist of at least six antennas, each six meters in diameter, operating primarily at wavelengths between 0.3 and 1.4 mm. The array will image the continuum and spectral-line emission from protostars, galactic nuclei, and solar system objects with an angular resolution in the range 0.1 to 10 arcseconds. The rms sensitivity at 0.3 mm wavelength (the shortest and most difficult operating band) for an integration time of 8 hours, velocity resolution of 1 km/sec, and angular resolution of 1 arcsecond is expected to be about 4 K. The sensitivity to continuum emission for the same integration time will be about 80 mJy.

Sub-millimeter observations are particularly sensitive to thermal emission from gas and dust, with temperatures in the range 10 K to 100 K. The powerful combination of high angular and spectral resolution spectroscopy offers the prospect of detecting and studying the gravitational motions in the gas around forming stars, the structure and motions of protostellar disks, and molecular outflows. The array will also be unique in its high-resolution imaging of neutral carbon lines at 0.37 and 0.61 mm wavelength. These lines, which have no

millimeter wavelength components, can reveal physical conditions extremely close to a hot star where molecular lines are absent due to photodissociation. Emission from carbon and excited carbon monoxide lines will provide new tools to probe the spiral structure of galaxies. Sub-millimeter measurements of quasars and AGN's will help to distinguish radiation mechanisms of radio-quiet and radio-loud objects. Molecular line observations of planets and satellites will give new understanding of planetary chemistry and weather.

Design and development of the Sub-Millimeter Array has been in progress since 1987. Sites on Mauna Kea and Mount Graham are being evaluated. The current schedule calls for completion of the array by 1996. Funds for the construction and operation are coming from the Smithsonian Institution. The array will be available to all qualified scientists based on peer-reviewed proposals.

### Long Range Programs and Technology Developments

Radio astronomy has historically advanced as technology was developed for measurements at shorter wavelengths, with more resolution, or with higher sensitivity. Our present frontier for new wavelengths is in the sub-millimeter, moving toward the far infrared. Quantum noise will stop this progression at about ten microns. Although radio astronomy is well developed at wavelengths longer than one millimeter, we expect significant advances at all wavelengths in the next decade.

At centimeter and longer wavelengths, the best receivers are either approaching the quantum noise limit or are so good that other sources of noise in the system will make the increase in sensitivity from further gains small. Cooled HEMT amplifiers will probably be the dominant type of receiver, and they allow much larger bandwidths than are commonly used now. Higher performance electronics for backends will make it possible to use these increased bandwidths to improve the sensitivity for continuum observations.

Even though improvements in individual receivers will not be large, the potential improvement in speed from multiple receivers in focal plane arrays increases directly with the number of receivers. Inexpensive, small HEMT amplifiers, possibly integrated in arrays, combined with less expensive backends will make multifeed systems practical. The first focal plane arrays have used multiple conventional feed horns, and therefore have a spacing of several beamwidths between beams. This approach is applicable to large area images, but overlapping beams which fully sample the focal plane also seem possible.

Although receiver technology at millimeter wavelengths approaches the quantum noise limit, there is much room for improvement. SIS receivers come within a factor of five of the quantum limit, but further development will be needed to achieve this level of performance over the whole millimeter and sub-millimeter band. Niobium junctions work well at wavelengths down to at least 1 mm, but higher temperature superconducting material such as niobium nitride will be better at shorter wavelengths. Better refrigerators are needed to make these receivers reliable and inexpensive to operate. Bolometers will be the radiometers of choice for single aperture continuum observations.

The most significant recent advances in antennas are seen in the design of the GBT which will have an unblocked aperture made possible with the use of modern structural analysis. The unblocked aperture will result in low ground pickup which will significantly reduce the system temperatures at lower frequencies and low side lobes which will allow more accurate measurements of the distribution of galactic neutral hydrogen. The GBT will also have surface panels accurate enough for millimeter wavelengths and remotely controllable adjustments for the panels. If suitable metrology can be developed for active surface control, operation at 2.6 mm wavelength will be possible in favorable weather.

Composite materials made of carbon-fiber reinforced plastic have revolutionized the design of sub-millimeter antennas. Inexpensive ways of fabricating accurate aluminum panels have also been developed, so that at millimeter wavelengths a cost-performance tradeoff must be made. The use of active surface control may allow building a very large antenna for millimeter wave operation. For much of the sub-millimeter band, operation above the earth's atmosphere is necessary—in an airplane, on a balloon, or in space.

**Advanced Computing Facilities:** The capability of computers continues to rapidly grow and their cost continues to fall. Evolving standards reduce the difficulty of sharing software, and the growth of networking will allow rapid access to images, easier exchanges with collaborators, and much more effective remote observing. New types of software will make searching for images and access to information from remote sites, easier and observatory operation more automatic. In the 1990's, radio astronomers will depend more than ever on high-performance computers to realize the full capabilities of their telescopes. This is especially true in planetary radar studies, pulsar research, and synthesis imaging where computers provide the "adaptive optics" needed to form correct images in the presence of corrupting effects of the earth's atmosphere. During the past decade, the computing needs of radio astronomical imaging have grown due to the large data volumes from array telescopes and from single-dish array feeds when used for spectroscopy. Moreover, the data processing required to extract all of the



information from arriving signals in the presence of atmospheric and instrumental fluctuations are highly CPU-intensive, and fast response is essential for many applications.

Progress in radio astronomy will depend as critically on fast, high-data-volume interactive computing as much as it will on low-noise electronics or advanced antenna design. In order to exploit the full scientific potential of the country's substantial investment in radio telescopes, and to remain competitive with the modern computing systems being found increasingly in other countries, it is important to make a wide range of advanced computing systems available at our national observatories and in our university laboratories.

The computing power that is best suited to analyzing different types of interferometer observations spans an enormous range. The simplest VLA and VLBA continuum projects can be processed using inexpensive workstations, but most VLA projects are best handled by machines with the interactivity and performance provided by "small supercomputers" or high performance workstations. Some spectroscopy and wide-field imaging projects still require the largest supercomputers available. No one location, or even type of location (observatory, university department, or computer center), is appropriate for all VLA, VLBA, and millimeter interferometer data reduction. The wide bandwidths expected on the national computer network in the 1990's will make it easier for resources such as software, data bases and computing cycles to be shared between the arrays and their user community. This will exploit the unique merits of workstations, small supercomputers, and large supercomputers to use each efficiently for different types of VLA, VLBA, and millimeter interferometer data processing.

**Meter Wavelength Astronomy:** Although radio astronomy began at meter wavelengths, the scientific potential of the long wavelength bands has barely been tapped, largely because of the difficulty in obtaining adequate resolution and the distortions introduced by the earth's ionosphere. Improved resolution is needed at meter and decimeter wavelengths to study the galactic non-thermal radio emission, the distribution of diffuse ionized gas in the Galaxy, the galactic halo, the interstellar plasma via the scattering and refraction of extragalactic sources, pulsar emission, "fossil" radio sources due to long lived synchrotron processes in galactic supernovae, radio galaxies and quasars, and non-thermal emission from the Sun and the planets.

In spite of these exciting scientific opportunities, for the past two or three decades meter wavelength radio astronomy has been outside the mainstream of astronomical research. Much more effort has focused on centimeter and millimeter wavelength research where it is easier to exploit technological advances to obtain good sensitivity and resolution. For a number of reasons, the situation is now changing. We now have a reasonable understanding of how to correct for propagation irregularities in the ionosphere, digital VLSI and modern computers make large array mapping techniques feasible, interference rejection techniques are beginning to be effective, and transmission of data over many kilometers is now cheaper and more reliable than in the past.

A 4-m wavelength receiving system is being developed for the VLA, and is expected to be in operation in time for the next sunspot minimum in the mid 1990's. But it is important to also begin now to develop techniques and prototypes for an array operating at even longer wavelengths, with a collecting area greater than  $10^5$  square meters and a resolution better than 10 arcseconds for both continuum and spectral line work. This can be done with a combination of university and national observatory collaboration, which will foster university development of techniques and the training of the next generation of telescope builders at the graduate and postdoctoral level.

In order to better image the wide range of phenomena that are observed at long radio wavelengths, resolutions need to be improved so that they are comparable with that of the VLA at centimeter wavelengths. This will mean establishing a program of space radio astrophysics during the next decade leading to the establishment of a Low Frequency Space Array, a free-flying hectometer wavelength synthesis array for high resolution imaging operating below the ionospheric cutoff frequency.

**Lunar Opportunities:** The Panel recognizes that over the next few decades national goals may lead to extensive exploration and colonization of the lunar surface. This may create exciting opportunities to build radio telescopes of very large dimensions. From the lunar surface it will be possible to observe at very low frequencies where the terrestrial ionosphere introduces increasing distortions as well as at very high frequencies where the earth's atmosphere becomes opaque. The far side of the moon, which is protected from man-made interference, is a particularly attractive site for low frequency radio astronomy. A particularly important use of the lunar far side will be as a base for interference-free SETI observations. We note with distress, however, that lunar orbiters and human activities, including radio astronomy research, on the far side of the moon, could generate their own RFI from telecommunication and computing devices. International agreements must be adopted in this decade to protect the far side of the moon for scientific research.

Lunar-based radio astronomy will be very expensive by normal standards, and probably cannot be justified during the next few decades in comparison with ground-based requirements. But if the country is committed

to a major presence on the moon for other reasons, then there will be exciting opportunities to do radio astronomy, first on the near side and later from the far side, that would otherwise not be possible.

**Sub-Millimeter Astronomy from Space:** The Large Deployable Reflector, a future space telescope for sub-millimeter and far infrared wavelengths, is being discussed by NASA which is supporting the development of reflector and detector technology. In order to successfully complete this innovative and difficult project, NASA will require access to the most advanced technology in the world. Many of the necessary developments are in progress in university and other non-NASA national laboratories around the country. The Radio Astronomy Panel urges NASA to support work in these laboratories both for the benefit of the LDR program and for the spin-off benefit to ground-based millimeter and sub-millimeter radio astronomy. The Panel also recognizes the need for the Sub-Millimeter Moderate Mission (SMMM) for an initial high resolution spectroscopic exploration of the full submillimeter band of star-formation regions and distant galaxies as a precursor to LDR.

**Radio Astronomy in Antarctica:** Due to the high altitude, extreme cold weather, and low water vapor content of the atmosphere, the Antarctic Plateau may be the best site on Earth for astronomical observations at infrared, sub-millimeter, and millimeter wavelengths. The Antarctic Sub-millimeter Telescope and Remote Observatory, (ASTRO), a consortium of AT&T Bell Laboratories, Boston University, and the University of Illinois, is scheduled to start operating a 1.7 m telescope at the South Pole toward the end of 1992. A larger consortium has proposed to establish a major Center for Astrophysical Research in Antarctica (CARA) which would ultimately include ASTRO, infrared telescopes; an experiment to measure the Cosmic Background Radiation anisotropy; and an advanced telescope project to develop detailed plans for a permanent observatory having several instruments, possibly including a 10-30 m sub-millimeter telescope. Scientific programs will include key problems in cosmology, star formation, and the physics and chemistry of the interstellar medium.

**Signal Processing:** Pulsar signals are highly dispersed, rapidly time variable, and strongly modulated in frequency. In some instances, these effects are a nuisance to be removed, or averaged; in others, they are the object of investigation. In all cases sophisticated signal processing must be done either in hardware or in software, or both. Special signal processors based on filter banks and autocorrelators have been developed over the years to carry out these investigations. There is a continuing need for such devices that operate with faster sampling rates, with more frequency resolution, and wider bandwidths. Such a processor can also serve the needs of spectroscopy, particularly dynamic spectroscopy of radio stars, and radar. Interface to a high-speed, high-volume recording medium is critical for pulsar searching.

At radio frequencies below about 1 GHz, dispersion is best removed by coherent techniques. Pulsar dispersions often exceed the chirp rates used in radar, so the commercial devices for de-chirping are not adequate for the pulsar task. Special construction efforts using, for example, VLSI techniques may provide a solution to this need. Pulsar searching can also be done by real-time signal processing since the data acquisition and analysis tasks are easily divided between microprocessors in a parallel or pipelined architecture.

**VLBI Recording and Data Transfer:** VLBI observations are limited in sensitivity by the capacity of the recording medium. Since the early 1970's commercial television tape recorders have been used for VLBI, and during the past decade inexpensive and reliable consumer type video-cassette-recorders (VCR's) have come into widespread use. The VCR-based system is cheap, flexible, and easily available, but the bandwidth is restricted to a few megahertz, or about two orders of magnitude less than that of the VLA at present. A broadband VLBI recording system for geodetic studies based on a commercial instrumentation recorder has been developed by the Haystack Observatory with NASA support and will be used with modifications for the VLBA. But the VLBA recording system is expensive and the bandwidth still limited to about 100 MHz. A competitive system has been developed by the Sony Corporation for use with the Japanese space VLBI mission, but has the same limitations as the VLBA system.

The bandwidth of the VLBA recording system can be improved by adding additional headstacs to the existing tape transports, but this will further increase the costs of construction and operation. Ultimately, fiber optics or satellites will be used to provide real time links, thus obviating the need for cumbersome transport and handling of tapes, but this must await the commercial installation of national and international broad-band data links. For the foreseeable future, VLBI will depend on physically transporting the recorded data to the correlator, and it will be important to develop new recording techniques to allow high density, broad bandwidth recordings that are both reliable and cost effective.

**Radio Frequency Interference:** Celestial radio signals are extraordinarily weak, often less than one hundredth of one percent of the internal receiver noise. As a result of the rapid growth in use of the radio spectrum, particularly from space and airborne transmitters as well as the dramatic increase in receiver sensitivity over the

past decade, radio astronomy observations are increasingly affected by interference. The protection of radio astronomy from man-made interference requires thoughtful spectrum management, careful observatory site selection, continued efforts toward site protection from internal as well as external sources of interference, and the development of techniques for reducing or eliminating the effects of interference from the received signals.

Optimum sharing of the radio spectrum with other services will require the participation of active radio astronomers in the regulatory and coordinating bodies such as the National Academy of Science Committee on Radio Frequencies. Because of the extreme sensitivity of radio astronomy receivers, it is often difficult to document specific sources of radio frequency interference. Special RFI search and monitoring stations, including at least one mobile station, should be established for this purpose. It is also important that radio astronomers use the most advanced technology available in order to best coexist with other users of the radio spectrum.

### Social, Political, and Organizational Considerations

#### *International Opportunities*

Modern observational astronomy has become so complex that no country can expect to have state-of-the-art instruments covering all parts of the spectrum and satisfying the needs of all types of observational programs. International collaborations present a wider variety of opportunities to individual scientists, permit the achievement of scientific objectives which may require a specific geographic location, provide an important forum for the interchange of ideas among people of different backgrounds and cultures on subjects that transcend scientific considerations, and may contribute to scientific and educational growth in developing countries.

*The Radio Astronomy Panel recognizes the potential opportunities resulting from international collaborations to develop major new radio telescopes that would not otherwise be feasible. The Panel encourages, where possible, that observing time on major facilities throughout the world be available on the basis of competitive proposals without regard to institutional or national affiliation.*

Perhaps the most straightforward form of international collaboration, and one involving a minimum of bureaucratic overhead, is the use of telescopes by visiting scientists from other countries. This not only provides observing opportunities that are otherwise not possible, but stimulates the exchange of scientific and technical ideas from which everyone learns and profits. Many research programs involve extensive and repeated observing sessions, as well as continued contact with colleagues having special technical or scientific expertise. These programs may be difficult to carry out by means of short observing trips, but will require extended periods of collaboration.

The VLA and VLBA, the upgraded Arecibo telescope, and the GBT will provide powerful observing opportunities for American radio astronomers at centimeter wavelengths. However, until the completion of the MMA, the Japanese and French-German IRAM millimeter wavelength facilities are likely to remain unmatched in this country. It has been the practice in the United States that observing time on radio telescopes at our national observatories and other major facilities be awarded without regard to nationality or country of residence, and the Panel recognizes the important role that this policy has played in maintaining the vitality of U.S. radio astronomy. It is hoped that the managements of foreign radio observatories will make the same opportunities available to U.S. radio astronomers, and that adequate funds be provided particularly to young scientists, to exploit these opportunities.

With the decreasing levels of worldwide tensions, the opportunity for international collaborations in the construction and operation of unique radio telescopes will become increasingly important. Careful attention will be needed to balance the opportunities for intellectual interaction and the savings in costs to individual countries with the bureaucratic and fiscal overhead that is not uncommon to large international projects. In developing plans for international cooperative projects, it will be important to minimize administrative constraints such as formulas for the distribution of observing time, for financial expenditures, for siting, or for the allocation of staff and management positions which are based on national affiliations rather than merit.

**Very Long Baseline Interferometry:** Radio astronomy has had a long and fruitful record of international collaborations such as the worldwide program in VLBI. The international cooperation in VLBI works because the science requires it. Moreover, since each country spends its money largely in its own country, complex spending formulae have not been a constraint. A number of major new VLBI facilities have been and are being built throughout the world as *national* efforts, but as part of the growing *international* VLBI network.

As a result of informal arrangements made by the scientists and observatories involved, any individual anywhere in the world can have simultaneous access to as many as twenty of the world's major radio telescopes

located in more than a dozen countries, including the USSR and China. This is done by submitting a single, simple proposal to one of several VLBI consortia, which will arrange for the observing time, the shipping of magnetic tapes across international boundaries and, often, even for the correlation of the tapes in one of several processing facilities operated in the United States and Europe. Image construction and analysis is done using common software which has been developed by a dedicated group of scientists working at a variety of institutions around the world, who have frequently migrated among the active VLBI observatories and who have freely exchanged the results of their labors. Logistical and technical coordination is handled primarily by the scientists involved with a minimum of administration from the managements of the observatories, and none from government administrators. The system works well, and the scientific results have been spectacular. But, during the next decade, major international collaborations involving national and commercial agreements will be established for space VLBI facilities such as Radioastron, VSOP, and IVS.

Most radio telescopes being used for VLBI are located in the northern hemisphere and give poor image quality for sources at low and southern declinations. A VLBI element located in South America is needed to complement the northern hemisphere VLBI networks and the VLBA. The optimum location is close to the equator in the western part of the continent, and several South American radio astronomy groups have expressed interest in developing a southern hemisphere VLBI facility. It should be possible for them to construct a suitable antenna from their own resources, but supporting instrumentation will be needed from the United States.

**The Large Southern Hemisphere Radio Telescope:** Due to the interdisciplinary and worldwide interest in the construction of a large aperture facility that will meet the requirements of radio and radar astronomy as well as atmospheric science, the funding and operation of a large southern hemisphere radio telescope is being discussed by an international group of potential partners. Political and economic factors suggest a novel funding scheme to tap resources, not normally available to the scientific community, to convert the existing foreign debt of the host country into development, construction, and operating funds. The advantages to the consortium partners include a unique scientific instrument available to the worldwide community, together with technology transfer and debt reduction to the host country. Because of the interest of its scientific community, the geographical location, and the economic and industrial capacity, Brazil is considered the most appropriate host country for the LSRT.

**Millimeter and Sub-Millimeter Astronomy:** The joint Max Planck Institut - University of Arizona German built sub-millimeter radio telescope to be located on a high mountain site in southern Arizona is expected to produce one of the most powerful sub-millimeter facilities in the world. A new collaboration between Caltech and the University of Toronto has been established to develop the expansion of the OVRO millimeter interferometer. Mauna Kea in Hawaii has two sub-millimeter telescopes: the James Clerk Maxwell Telescope, (JCMT) operated by the UK, Canada, and the Netherlands, and the Caltech Sub-millimeter Observatory located 150 meters away. These two telescopes as well as the Smithsonian Sub-Millimeter Array may be used together for high resolution interferometric observations of star-forming regions and nuclear regions of galaxies as well as other compact sub-millimeter emission regions.

#### *Balance Between the National Observatories and University Facilities:*

Radio astronomy is an experimental science. Traditionally many of the most important discoveries were made directly as a result of new instrumentation built by skilled and devoted experimentalists. Today, the wide variety of astrophysical problems being studied by radio techniques requires both the national facilities that can support a broad spectrum of users as well as smaller innovative research facilities in which technologies of the future can be developed.

*The Panel is concerned about the inadequate opportunities at university operated facilities for the development of new instrumentation, increasing pressures on the remaining facilities to operate more and more in the mode of the large national user facilities, and the decreasing opportunities for the training of scientists skilled in instrumentation.*

The availability of powerful national research facilities to individual scientists has resulted in the proliferation of small (one to three people) but viable radio astronomy groups in many university astronomy or physics departments that do not have their own observing facility. At the national observatories and large university-operated facilities, the instrumentation is often complex and at the state-of-the-art. The development of new instrumentation for these telescopes is generally the responsibility of professional engineers with little understanding of, or even interest in, the end use for astrophysical research. Nevertheless, the interested and

capable scientist can exploit the tremendous technical resources at the national observatories and individually contribute significantly to the development of advanced instrumentation and techniques.

At the university observatories, the instruments are often, but not always, smaller, less expensive, generally more specialized, and have a smaller user base than those at the national centers. In principle, the university facilities provide a qualitatively different research environment which encourages a more experimental approach by talented researchers, including graduate students and postdoctoral fellows, who are highly motivated and have few other duties to divert their attention and effort from research. With less pressure on the efficient use of observing time, it is possible for an observer to modify a program or equipment in response to early results or to try something new or different. In the event of failure, the experiment can be repeated as needed. The environment is also ideal for long-term projects requiring repeatability, specialized equipment or techniques, or unusual scheduling.

A consequence of the construction of major new research facilities at the national centers has been the closing of smaller university instruments. Moreover, many of the traditional differences between the national centers and the larger university-operated observatories are becoming less distinct. As operating funds have become more restricted, the university groups are driven into alliances with other groups by forming small consortia, they are encouraged to support visiting observers as a condition to funding, their scheduling procedures become more formalized, and their operation assumes much of the flavor of large national observatories.

There is also increasing pressure for national radio observatories to expand their traditional role of operating only expensive, unique instruments and to begin operating smaller observing facilities as well. The operation of user friendly observing facilities is expensive, and the Panel believes it is not cost effective to provide extensive user support to small or modest sized facilities. The long-term health of radio astronomy requires proper balance between large unique facilities at the national centers and the smaller, but often also unique, facilities where many important discoveries are being made, where innovative new techniques are being developed, and where the next generation of observers and telescope builders is being trained.

**Student Training:** Most of the developers of new instruments and telescopes have received their training in the universities and institutes which operate their own facilities. But, there are now only a few remaining facilities involved in student training. The Panel is concerned about where the next generation of instrumentalists will come from—the men and women who will design and develop new facilities needed to maintain the country's preeminent position in radio astronomy.

The lack of suitable facilities for training technically oriented radio astronomers is exacerbated by a lack of well-defined career paths for people more interested in building instruments than using them. Moreover, low salary levels for needed professional technical support at our university and national center facilities have contributed to the loss of key personnel that will be increasingly felt in future years. As a result, many of the key positions in radio astronomy in this country are being filled by scientists trained in other countries. It is important for the future of radio astronomy in this country that universities with plans and ideas for the development of new telescopes, new techniques, or other new instrumentation be adequately supported, and that the university observatories and national observatories recognize the contributions of instrumentalists as well as users in their professional staffing and promotion policies.

#### *Agency Funding and Management Policies:*

The rapid growth of radio astronomy in the United States began in the late 1950's with encouragement and financial support primarily from the Office of Naval Research, the Air Force, and later from the National Science Foundation. The field enjoyed substantial growth throughout the 1960's and early 1970's, but starting with the adoption of the Mansfield Amendment in 1968, DoD funding for radio astronomy has greatly diminished and the NSF has had to assume essentially all of the support for radio astronomy. The growth of radio astronomy has continued in the 1980's, as measured by construction of new radio telescopes, increased numbers of students and active radio astronomers, the development of new and more powerful ancillary equipment and techniques, and research activity in general. But NSF support for radio astronomy has not continued to grow, and in fact has not even kept up with inflation. In terms of purchasing power, NSF funding of astronomy today is almost identical to that in 1977. But the demands on those funds are very much greater today than they were in 1977. Every institution and every individual that depends on the NSF for research support is affected by this. It is a major problem for all of astronomy.

Today, there are more people doing astronomy than ever before. New instruments have been built and put into operation, university research groups have increased in numbers and in size, and in numbers of students. This growth is driven by many factors, including the general population growth, but especially the challenges and excitement of the field; and it is appropriate that it should grow. How has this increased activity been sustained at the same time NSF funding has been constant or declining? More than a dozen radio telescopes have been

closed over the past two decades to make way for new ones; NASA has increased its astronomy grants; and there has been some increase in state and private support of astronomy. All of these have helped a little, but basically the constant NSF budget is being spread more thinly over an ever increasing number of people and activities.

Radio astronomy is particularly affected by the inadequate level of NSF support because it is essentially a ground-based science and thus receives much less NASA support than other fields of astronomy. Moreover, the mission-oriented nature of NASA support is not a substitute for the NSF supported activities which are based on peer review without regard for the need to satisfy specific programs, missions, or national goals.

It is of course reasonable to close obsolete or ineffective facilities in favor of new ones. This has been and will continue to be done, but it is not enough. If ground-based astronomy is to survive and flourish it needs both a reasonable influx of capital investment in new telescopes and equipment, and an expansion of operating and grant support at least consistent with the natural growth of the field. There is no reason why *ground-based* astronomical research in the United States should shrink as a fraction of the total intellectual and cultural base, nor should it shrink relative to world science and astronomy in general; but both of these are now happening.

Good science is a highly individualistic effort, and the administrative system should impose a minimum of management or control beyond that necessary to assure reasonable accountability. The NSF has historically supported individual scientists based on peer review of proposals and without regard to the need to satisfy specific programs or missions. The NSF also supports major national facilities such as NRAO, NOAO, and NAIC, but provides no scientific control or management, leaving this to the Observatory Directors, the managing consortia, and their advisory committees.

NASA, by contrast, is heavily mission oriented with a tradition of strong program management. This may be appropriate for major space missions where design, construction, and operation phases may last as long as twenty years, and where a highly coordinated central management is needed. But, we are concerned that policies which have been formulated to insure the success of expensive complex space missions are also applied by NASA to the administration of scientists and science programs which are not directly related to the preparation and operation of actual space missions.

The current disparity between the NASA and NSF budgets allows NASA to make important contributions to ground-based astronomy that normally would be in the domain of the NSF. But we note that fundamentally important areas of ground-based radio astronomy are being funded out of "small change" from other, essentially unrelated large NASA space missions. This has led to striking anomalies in what gets done and what doesn't get done and to a possible distortion of priorities.

Due to the large difference between the scale of NASA and NSF funding, the dollars are driving the science rather than the other way around. Individual scientists are increasingly submitting proposals to use space facilities or proposals to access space data banks, because that is where the money is. Good science is done, but this may create the illusion of greater demand on these facilities, and in turn helps to generate even more financial support for these activities. This may appear to be attractive in the short term, but may have long-term, adverse implications for the progress of astronomy. It is driving scientists to pursue work related to NASA missions and NASA money, or related to broader national or agency policies such as the establishment of a space station, or a return to the moon, rather than where their scientific curiosity directs them. As a result, some astronomers are being driven away from ground-based astronomy to space astronomy, and this may have particularly serious consequences for radio astronomy.

*The Panel is concerned about the deteriorating level of support for individual scientists and recommends a restoration to earlier levels of the traditional NSF research grant support. Particular attention must be paid to young scientists who are finding it increasingly difficult to break into the funding system.*

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## Report of the Infrared Panel



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